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RESPONSE OF SELECTED MATERIALS TO HIGH-SPEED FRAGMENT IMPACT

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1. BACKGROUND

This paper was motivated by the Army Aircraft Protective Shelters Program and is one of four papers by Waterways Experiment Station personnel dealing with this subject. During the early phases of the Aircraft Shelters Program it became evident to researchers that sufficient information dealing with the mechanics of fragments and the defeat of fragments by various materials was not readily available. A study of fragment mechanics and the effect of fragments on various materials was conducted to provide designers with facts that could be used in solving the protection problem.

2. OBJECTIVES

The eventual objective of the study of fragment mechanics was to obtain information on the ability of various materials to stop the penetration of fragments from indirect fire weapons and to define the optimum orientation of these materials whether used singularly or in combination with each other. Before this main objective could be realized, several intermediate goals had to be reached. A logical method of simulating a fragment by some standard projectile had to be selected, and a facility for propelling the projectile under closely controlled conditions had to be constructed. Researchers had to choose, from among a large number of possible protective materials, those few that best met Army needs regarding availability, cost, weight, ease of construction, and effectiveness. A test program had to be conducted and the accumulated data had to be analyzed in order to categorize the best of the available data. Those materials showing promise in the laboratory were selected for full-scale field testing. This paper describes the handling of each of these steps and lists the conclusions drawn from each phase of the work.

3. DESCRIPTION OF PHYSICAL FACILITIES

A fragment-simulation facility was constructed and equipped with several firing devices. A capability exists for firing several different sizes and shapes of fragment-simulating projectiles ranging

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in weight from 17 to 305 grains. Most of the data collected and analyzed were obtained from the firing of a 21-grain steel cube measuring 0.218 in. on a side. This cube resembles fragments from several types of mortar rounds in various ways. It has sharp corners and lines and a small sectional density which makes it aerodynamically inefficient (Figure 1). The cube is not spin stabilized, and the 21-grain weight classes it with a wide range of fragments from both domestic and foreign mortar and rocket rounds (Reference 1). Unlike a true fragment, however, it is not hot. This could be of some significance in evaluating its effect on certain textiles such as ballistic nylon.

4. ANALYSIS OF MATERIAL RESPONSE TO FRAGMENTS

4.1. Behavior of Textile Filaments Under High-Speed Impact.

Considerable theoretical work has been done regarding the behavior of textile filaments under high-speed tensile impact (References 3-5). Some of the results of this work are useful in explaining the method by which ballistic nylon defeats fragments and in determining the best amount and orientation of the material.

When a high-speed fragment strikes a nylon filament, the filament responds by moving in the direction of the fragment motion if the fragment velocity is not too high. This motion creates a transverse wave in the filament, and, simultaneously, two tensile strain waves propagate down the filament in opposite directions from the point of impact. The configuration of the filament prior to breaking is shown in Figure 2.

In Figure 2, Point I is the impact point of the fragment and Point A shows the position of the head of the transverse wave. Point C indicates the front of the tensile wave while Point B shows the end of this wave. Point D indicates material that is neither strained nor moving with the transverse wave.

The velocity, U , of the transverse wave front at A is related to the tension, strain, and density of the filament by

$$U = \sqrt{\frac{T}{M(1 + \epsilon)}}$$

where

U = velocity of transverse wave

T = tension in the filament

M = linear density of the unstrained filament

ϵ = strain of the filament

Here U is expressed in Lagrangian rather than fixed coordinates. It is evident from the formula that whenever the local strain at the projectile is large enough to produce rupture of the filament the tension drops to zero, and the transverse wave no longer propagates. Thus, the amount of filament moving in the transverse wave and the amount of energy absorbed to produce the transverse wave are highly dependent on the time at which rupture strain is reached.

In addition to the loss of energy required to produce the transverse wave, the fragment also transfers energy to the filament in creating the tensile strain wave. Because of the interdependence

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of the transverse and tensile waves, the rupture of the filament also causes an end to the propagation of the strain wave. Thus, the rate of strain, which is directly proportional to the velocity of the fragment, is very important in determining how much energy is transferred from the projectile to the filament before breaking.

One other important fact should be considered in describing the behavior of the filament during transverse impact. There is a velocity limit on the propagation of the transverse wave. This velocity limit has been termed the critical velocity, and when a filament is struck by a projectile with this velocity, the rate of strain is so high that the local strain becomes sufficient to produce rupture before the transverse or tensile waves are formed. The projectile shears through the filament immediately upon impact and the only energy lost by the projectile is that required for the shearing mechanism.

These ideas allow one to identify three distinct response patterns of a textile to a transverse impact. These response patterns are designated as tensile, transitional, and shear response. The characteristics of each response type are presented herein (Figure 3).

4.1.1 Tensile Response: At low impact velocities (1200-fps range) the local strain around the projectile does not reach the level required for breaking the filament until the entire filament has responded in tension and transverse motion. This is the response area that absorbs the maximum amount of fragment energy. Some textiles, notably nylon, can absorb very large amounts of energy at this rate of strain. The total amount of energy absorbed prior to rupture of the filament depends on the mass of the filament and its specific breaking energy (the area under the tension-strain curve from no strain to rupture strain). These are physical parameters that can be evaluated for various textiles and used in comparing their relative energy absorption characteristics.

4.1.2 Transitional Response: At intermediate velocity levels the transverse wave can form and begin to propagate. Some material is put into tension and part of the filament is set into motion. But the rate of strain is much higher than the rate of propagation of the transverse wave, and breaking strain is reached before the entire filament responds. This response absorbs less energy than the tensile response but, for nylon, the energy absorbed is still quite large.

4.1.3 Shear Response: Whenever the impact velocity is sufficiently high the filament will not begin to transmit the transverse wave before the local strain is sufficient to produce breaking. This velocity is called the critical velocity and, at or above the critical velocity, the filament shears immediately upon impact. No transverse or tensile waves are formed, and the energy absorbed during this penetration is minimal. The energy absorption at this velocity is so low that a textile should not be used to defeat fragments if fragment velocities higher than the critical velocity are anticipated.

4.1.4 Summary: From the above information it is seen that

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for a textile material to be effective in defeating fragments it should possess the following characteristics: (a) the critical velocity should be high, (b) the material should stretch for a high percentage of its length before breaking, and (c) the level of energy required to stretch the fiber should be high. Table 1 (taken from Reference 4) shows that nylon possesses a better combination of these characteristics than do other synthetic fabrics.

TABLE 1 CRITICAL VELOCITY, ELONGATION, AND ENERGY FOR VARIOUS PROTECTIVE MATERIALS

Material	Transverse Critical Velocity	Breaking Elongation	Specific Breaking Energy
	fps	%	joules/gram
Acetate	1115	30.7	34.9
Glass fiber	1420	2.6	8.1
Nylon	2240	11.1	38.5
Polyester	1830	8.0	24.3
Rayon	1465	13.1	25.8

4.2 Empirical Data on Ballistic Nylon. A large number of tests were conducted to evaluate the fragment-defeating capability of ballistic nylon. This material is referred to in many supply channels as "Federal Stock Number 8305-261-85 1b, cloth, ballistic, nylon, basket weave, 13.5 oz minimum, 15 oz maximum wt/sq yd." A 12-ply flak blanket with grommets and exterior weatherproof cover weighs approximately 21 oz/sq ft and the procurement cost is approximately \$3.60/sq ft.

Various sample thicknesses and orientations were tested in the fragment-simulation facility. Projectiles were fired at the samples from a distance of 12 ft, and velocities of the projectiles were chronographed in front of and behind the sample. This arrangement allowed a determination of both the velocity needed to penetrate the sample and the velocity loss that the projectile sustained when the striking velocity was high enough to cause penetration.

The results of some of the tests have been used in preparation of Figure 4. All these curves are based on velocity change of the 21-grain cube when impacting the nylon at right angles. Notice in these curves that the nylon shows a decreasing velocity loss, and hence a decreasing loss of momentum, with increased striking velocity. However, the nylon absorbs almost constant energy over a wide range of striking velocities. It is assumed that this is the broad range of maximum tensile response. When the striking velocity is high enough to keep the projectile moving in the material at more than 2300-2400 fps, the effectiveness of the nylon has declined sharply.

In addition to these tests with the projectile impacting loose-hanging material at a 90-deg angle, the material was also

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tested at various impact angles, tested while wet, under slight tension, and using separation of the plies to produce air space between the layers of the blanket. No curves are given for these tests as they showed no important changes in the behavior of the nylon. The results are summarized as follows:

- a. The loss in velocity that the projectile sustains when penetrating a ballistic nylon blanket decreases if the projectile maintains velocities of above 2200 fps while passing through the blanket.
- b. Doubling the thickness of a nylon blanket will not double its effectiveness in stopping fragments.
- c. There is no change in the effectiveness of the nylon if it is angled up to 45 deg relative to the path of the projectile.
- d. There is no change in the effectiveness of the nylon if it is hanging loose or under slight tension.
- e. Wet nylon is as effective as dry.
- f. Air gaps between individual or groups of nylon layers do not increase the effectiveness of the blanket.
- g. At velocities greater than 2000 fps the projectile will lose as much velocity in 10 ft of air as in passing through four layers of standard nylon.
- h. The projectile can be stopped in 32 plies if its striking velocity is near critical. Adding layers beyond 32 plies gives diminishing returns. Test results showed that the mortar fragment that could penetrate 32 plies could generally penetrate 64 plies as well. This indicates that the nylon blanket is effective in the low-velocity regions (below 2200 fps) and adding plies does not increase this effectiveness enough to offset the additional cost and weight.

4.3 Tests on Plywood. Both a 21-grain cube and a 305-grain cylinder were used in studying the response of 3/4-in. fir plywood. The curves in Figure 5 summarize the tests. Note that, unlike ballistic nylon, the response of the plywood seems to be independent of the velocity of the projectile. The velocity loss that the projectile sustains when passing through the plywood is nearly the same over a very broad range of velocities. Also, the effectiveness of the plywood is nearly linear with thickness.

The fact that plywood causes a constant velocity loss regardless of impact velocity while the ballistic nylon loses its effectiveness with increasing impact velocity is the basis for the following suggestion concerning orientation of plywood and nylon. If these are used in combination, the plywood should be placed in front of the nylon. This enables the velocity to be reduced by the wood to the velocity region where the nylon becomes effective. This fact is clearly seen in Figure 6.

4.4 Shots on Sand and Clay. Tests were run on both dry and saturated sand in order to gain some idea of its effectiveness under general outdoor conditions. These sand samples were contained in 1-cu-ft boxes made from 1/2-in. plywood. The sand, either wet or dry,

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proved highly resistant to penetration by the 21-grain cube. The curves in Figure 7 illustrate the effectiveness of the sand in stopping fragments, and they also show the tendency of the projectile to reach a maximum depth of penetration at approximately 3000-3500 fps. Increased velocity from this point does not yield increased penetration.

Tests and preliminary mathematical investigations indicate that the response of sand to fragment impact may also be divided into three different areas depending on the fragment velocity. In the range of velocities below 1500 fps the sand tends to absorb the projectile energy by compression. Throughout most of this velocity range the sand can transmit a shock wave faster than the projectile is moving; hence the load is distributed over a large area, depending on the angle of internal friction of the sand. At velocities from 1500 to 3500 fps the fragment seems to truly penetrate the sand rather than compress it. The fragment is moving through the sand faster than the sand can propagate a compressional wave, so there is no major spreading loss. The only resistance encountered by the projectile may be that required to move the grains of sand far enough apart to effect penetration. At these velocities (below 3500 fps) the classical equation of Poncelet-Petry can be used to approximate the depth of penetration of the fragment:

$$D = \frac{w}{a} k \log_{10} \left(1 + \frac{v^2}{215,000} \right)$$

where

- D = total penetration distance (ft)
- w = projectile weight (lb)
- a = cross-sectional area (sq in.)
- k = constant depending on soil type
- v = velocity (fps)

The range of velocities above 3500 fps shows different phenomena. There are indications that a significant amount of heat is created. Also the inertia of the sand at this loading rate is high enough to prevent the movement of the sand, so that it is pulverized and reduced to the fineness of powder. At this rate of loading it is felt that the problem requires consideration of the Rankine-Hugoniot equation of state before a solution is attempted.

The shots into clay showed other interesting tendencies. The impact of the projectile into a clay sample would cause a void in the clay in the shape of a cone with the projectile stopping in the vertex (see Figure 8). There is practically no change in the depth of this cone with a change in striking velocity. However, the volume of the cone increases with increased striking velocity. The energy of the projectile seems to be expended both in penetration and creation of the cavity, and the latter becomes more important as velocity increases. With a suitable choice for the constant, k, the Poncelet-Petry equation may also be used for clay. However, a general mathematical description of the penetration problem for clay, like that for sand, is still unavailable.

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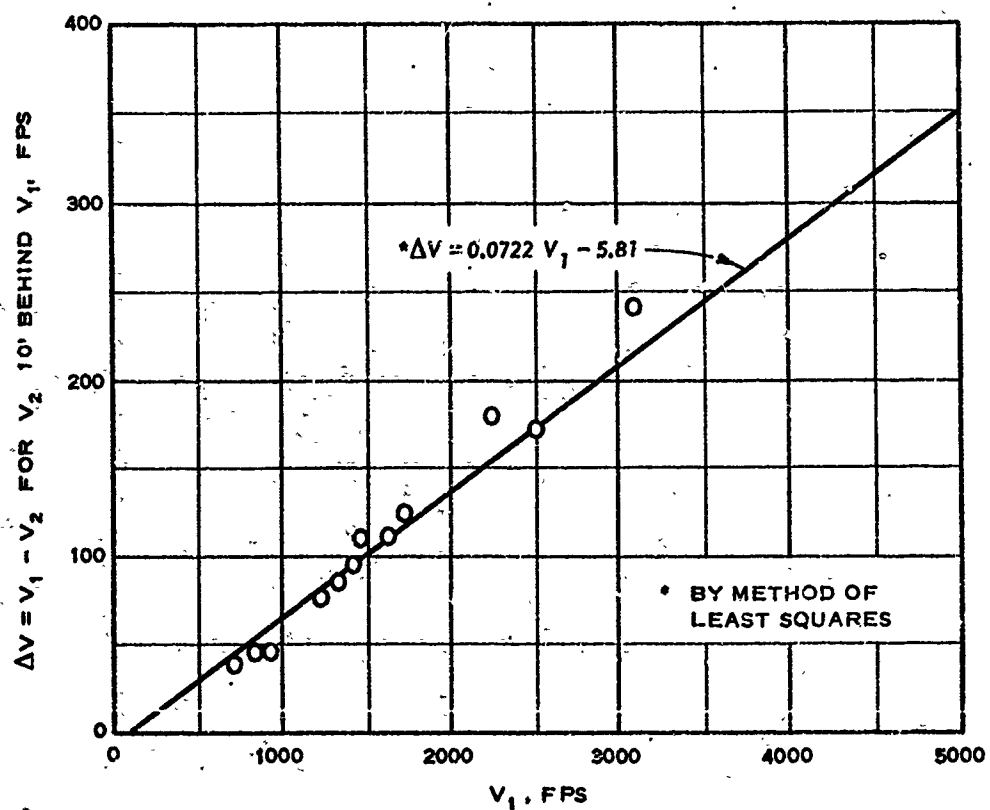


Fig. 1. Velocity loss for 21-grain cube in air

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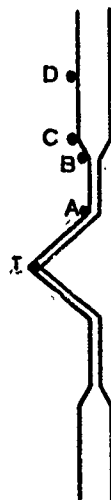


Fig. 2. Filament configuration after impact

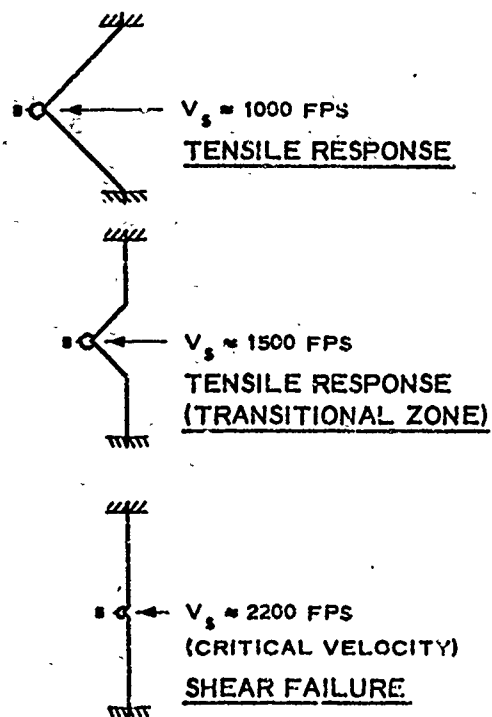


Fig. 3. Failure patterns for nylon filament

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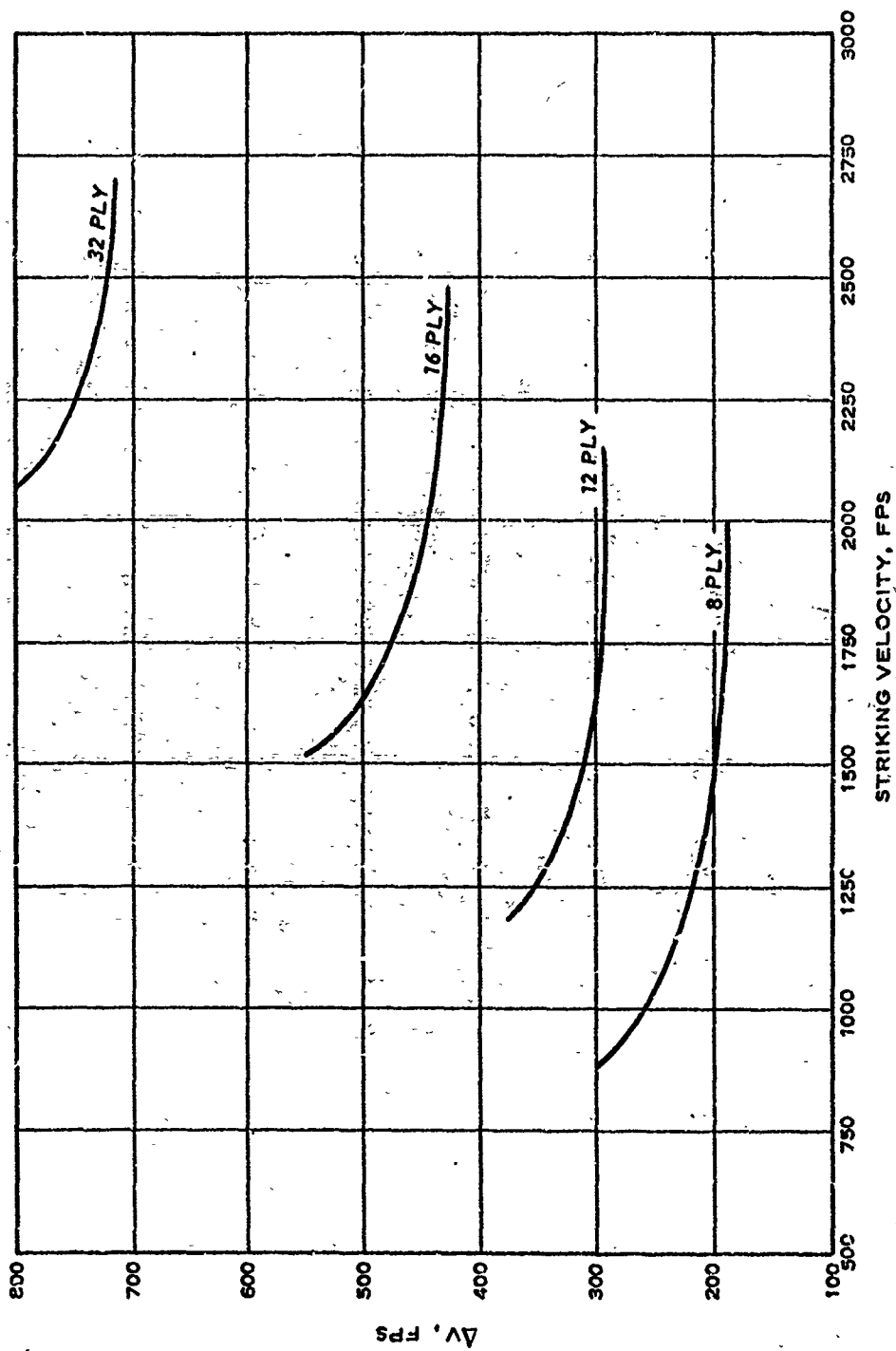


Fig. 4. Velocity loss for cube in nylon

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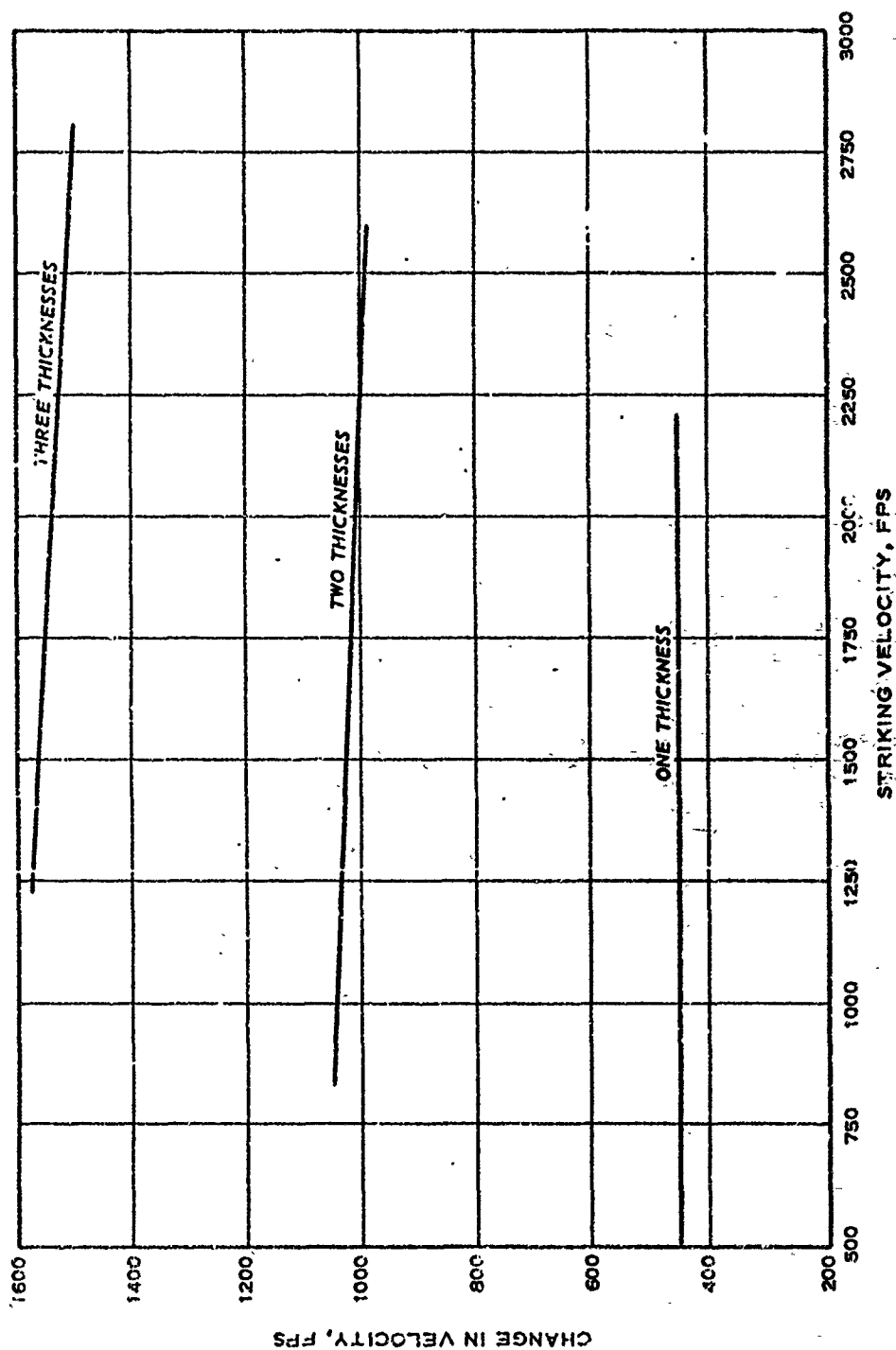


Fig. 5. Velocity loss in 3/4-in. plywood

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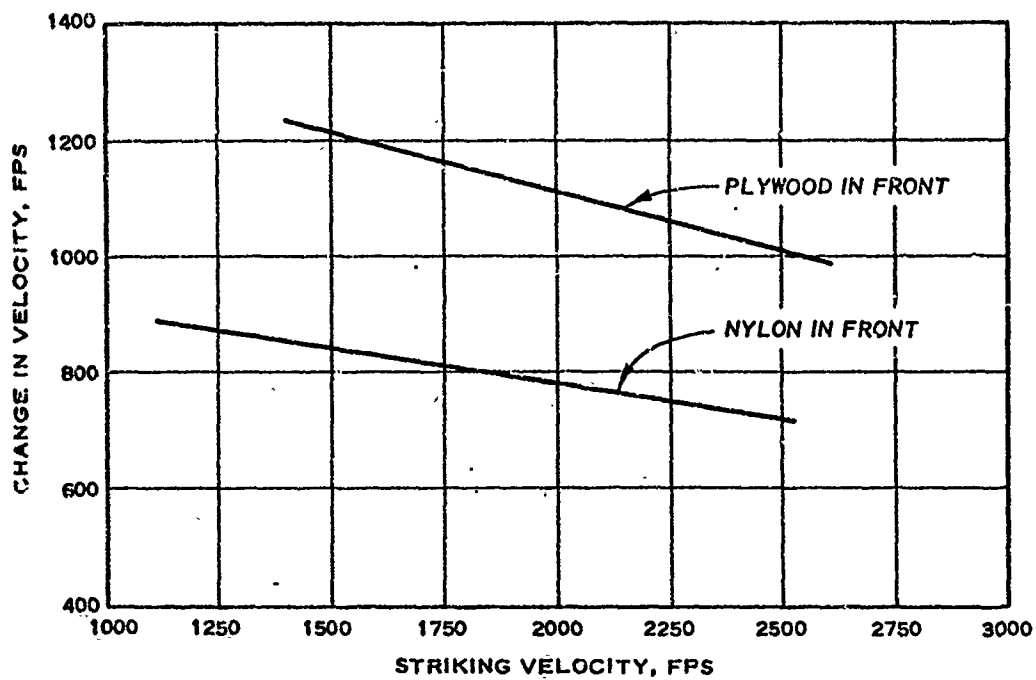


Fig. 6. Velocity loss in nylon/plywood combination

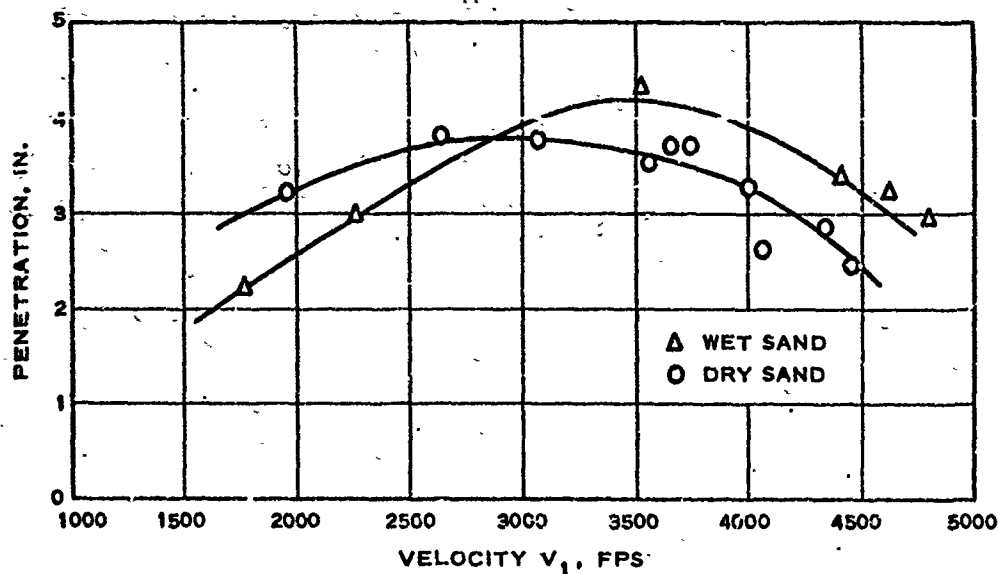
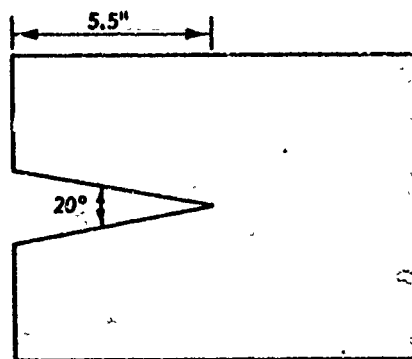
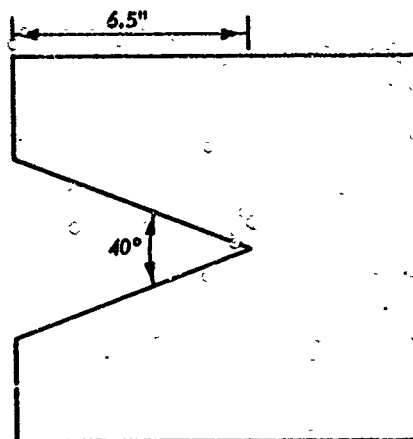


Fig. 7. Penetration of cube in sand

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IMPACT VELOCITY
2000 FPS



IMPACT VELOCITY
4000 FPS

Fig. 8. Behavior of clay upon impact